

Optimal carbon taxes for China and implications for power generation, welfare, and the environment

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ABSTRACT

China is expected to constitute about half of the world's emissions between 2010 and 2040. As concerns about climate change intensify, the Chinese government is poised to commit to a low carbon economy. These conditions make China a suitable case in which to study how emission policies impact on energy supply, welfare, and the environment. To achieve this purpose, we incorporate abatement technologies into the GTAP computable general equilibrium model and show that optimal taxes range between 0.03% for services and 2.02% for manufacturing. In most cases, simulated tax rates are by far higher than pollution taxes stipulated in the new Chinese environmental tax law. Furthermore, despite a decline in output of many sectors including the electricity sector, overall welfare gains exist from introducing carbon taxes. Moreover, these taxes reduce environmental pollution by approximately 62.5%. In general, carbon taxes are insufficient for mitigation in China, and due to a coal-dominant energy structure, implementing these taxes leads to a decline in power generation. Hence, the Chinese aggressive investment strategy for renewable electricity technologies as stipulated in its 13th Five-Year Plan is understandable.

1. Introduction

China accounts for the world's largest carbon emissions driven primarily by the country's huge reliance of coal and other fossil energy. According to NEAA (2015), China, at present, constitutes approximately 30% of the world's carbon emissions. Besides, China compared with many other countries, accounts for a very high growth rate and it is expected to constitute approximately half of the world's projected emissions between 2010 and 2040 (Carson et al., 2014).

The above conditions make China a suitable case in which to study the manner in which emission policies would influence Chinese power supply, welfare, and the environment.

As the global clamor to reduce carbon emissions persists, the Chinese government is taking serious care to design energy policies for the future and the issues of economic growth driven by a limited use of carbon and fossil fuels would foundation these policies. In the 12th Five-Year Plan of the Chinese government, there is an ambitious commitment to reduce carbon emissions. As compared to the carbon emissions level in 2005, a 40–45% cut per unit output has been proposed by the year 2020 (Lin and Wesseh, 2013a; Wesseh and Lin, 2016a). The recent Paris Conference on climate change in 2015

prompted the Chinese government to further raise this target from 40% to 45% to between 60% and 65% and to peak emissions by the year 2030. As a means of achieving these goals and promoting energy supply security, Chinese central planners and academicians have demonstrated enormous interest in environmental taxes and the expansion of clean energy and its potential replacement for fossil-related energy sources. For instance, the Chinese new environmental tax law which is due to come into effect in January 2018 stipulates the taxing of air and water pollutants at rates beginning at \$ 0.17 and \$ 0.20 per unit, respectively. A monthly tax ranging from \$ 50 to \$ 1612 has also been stipulated for noise pollution.

The objectives of this paper are therefore threefold. First, an attempt is made to calculate optimal¹ emissions taxes for China. Second, the model is readjusted to test the economy-wide and environmental consequences of implementing the calculated taxes in China. Finally, the results are combined to discuss their implications for clean energy expansion in China.

As may be noticed from the review of studies presented in the next section and to the authors' best knowledge, this paper happens to be the first-of-its-kind approach to the application of real and more appropriate data for carbon policy design for China. In other words, our study

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¹ Optimal taxes in this study refer to the minimum tax rates that fully internalize environmental damages.

is the first one which utilizes more recent Chinese-specific sectoral abatement data to design and study optimal carbon fees and to explain their implications for clean energy development in China. Our modeling technique also adds value to the literature by incorporating abatement technologies into economic modeling.

The rest of the study proceeds in the following manner: The literature and how it addresses the problem is presented in [Section 2](#). Sources and descriptions of the applied data are documented in [Section 3](#). [Section 4](#) describes the methodology employed in our research and explains their applications. [Section 5](#) summarizes results obtained. Relevant discussions of the results and implications for Chinese clean energy policy are presented in [Section 6](#). [Section 7](#) draws the conclusions.

2. Relevant literature

Carbon taxes and the development of clean energy technologies have been instituted in many parts of the world for the purpose of limiting and controlling carbon dioxide emissions. From a global perspective, the carbon tax literature is diverse. From comparing the manner in which carbon taxes perform in relations with other mechanisms for abatement to comparing trends in emissions fees, from economic impacts of carbon taxes to environmental considerations, the literature seems broad.

The first strand of studies is the one that compare the performances of various options for mitigation. The general conclusion from these studies is that a carbon tax is a superior mechanism for abatement. Notable examples of these studies include: [Weitzman \(1974\)](#), [Pizer \(2002\)](#), [Dasgupta and Heal \(1979\)](#), [Nordhaus \(2006\)](#), and [Zakeri et al. \(2015\)](#).

The trends in carbon taxes have also been the focus of several researchers. [Sinclair \(1992\)](#) asserts a decline in the rate of carbon taxes. [Ulph and Ulph \(1994\)](#), however, questioned the reliability of Sinclair's findings and argue a rise in carbon taxes in some cases. Following similar research direction, [Hoel and Kverndokk \(1996\)](#) produced the same conclusions as [Ulph and Ulph \(1994\)](#). Few other studies (e.g. [Farzin and Tahvonen, 1996](#); [Van der Zwaan et al., 2002](#); and [Bosetti et al., 2011](#)) have produced mixed conclusions between [Sinclair \(1992\)](#) and [Ulph and Ulph \(1994\)](#).

There are studies that also highlight the designing to optimal carbon taxes including but not limited to [Farzin and Tahvonen \(1996\)](#), [Perroni and Wigle \(1997\)](#), [Alton et al. \(2014\)](#), and [Duan et al. \(2014\)](#).

Finally, the aspect of the literature that constitutes the vast majority of studies is the part that considers the consequences of introducing a carbon tax. Findings from these studies are mixed with conclusions suggesting that carbon taxes could reduce emissions in some cases and fail in other cases. Also, welfare implications of carbon taxes are also mixed in the literature, and hence, an appropriate execution of carbon tax recycling is recommended. The most recent publications supporting these conclusions include: [Liang and Wei \(2012\)](#); [Fang et al. \(2013\)](#); [Dissou and Siddiqui \(2014\)](#); [Marie \(2014\)](#); [Liu and Lu \(2015\)](#); [Chen et al. \(2015\)](#); [Li and Lu \(2015\)](#); and [Wesseh and Lin \(2016b\)](#). For a more detailed review of this literature, interested readers are referred to [Wesseh and Lin \(2016b\)](#).

For China in particular, the impacts of implementing carbon taxes have been assessed recently by few authors. [Duan et al. \(2014\)](#) constructs a model of Chinese energy economy and environment in order to evaluate optimal trend in carbon taxes. The authors find that the optimal carbon tax rates for China demonstrate evidence of an increasing monotonic function. [Li and Lu \(2015\)](#) use TIMES model to project Chinese cement demand and study how carbon taxes influence China's cement industry. The authors find that, in the short-run, the implementation of carbon taxes does not influence technology choices. However, a high carbon tax appears to increase the application of production with CCS or waste heat recovery in the long-run. [Chen and Nie \(2016\)](#) apply an optimal welfare model to study the effects of a

carbon tax on social welfare in China. The authors find that carbon taxes raise social welfare from a production perspective and lower social welfare from the consumption and redistribution perspectives. [Wesseh and Lin \(2016b\)](#) compute optimal emissions taxes from a global perspective including China and found that carbon taxes reduce environmental damages by nearly 50% on average. [Dong et al., 2015](#) employ CGE model to evaluate the impact of a carbon tax on Chinese carbon dioxide reduction and the economy in general. Their results point to evidence of significant reductions in carbon dioxide but report economic losses under all scenarios.

From the review of studies described above, one would realize that the literature in general has produced mixed results. Some studies point to economic and environmental gains from implementing carbon taxes while other studies argue on the contrary. In terms of China in particular, the literature has mainly employed theoretical wisdom to simulate optimal trends in carbon taxes on an aggregate basis. In other words, these studies have failed to use actual abatement data disaggregated by polluting sectors. These limitations undermine the effectiveness and optimality of the kind of taxes that have been simulated in the literature, especially for studies focusing on China. A notable exception, however, is found in [Wesseh and Lin \(2016b\)](#) who use actual abatement data to address the problem. Notwithstanding, despite the contribution of their study especially for results reported for the United States, it is worth mentioning also that they use US industrial data as a proxy for other countries and regions. The assumption that US abatement technologies could represent the situation in other countries is somehow strong and could be misleading in some respect. In addition, be it the United States itself or other countries, the data used appear to be somehow outdated given that they were collected for the year 1993.

Against this backdrop, a study of this nature which utilizes a more recent and actual Chinese abatement data in combination with other macroeconomic variables (see [Section 3](#)) is not only necessary for Chinese energy and environmental policy designs, but could as well add value to the somehow inconsistent literature on carbon pricing and their general impacts. This should not be taken for granted especially when such inconsistency is attributable, in part, to the applied data and modeling techniques.

3. The data

In order to derive optimal carbon taxes for carbon-constrained China, this study collects and employs environmental damages and abatement data for various polluting sectors of China. Damages and abatement data for China are collected from [Labriet and Loulou \(2003\)](#). In addition, data on output per sector, sectorial government spending, and sectorial private sector spending, are included to provide for a more complete analysis. These data are taken from the version 8 database² of the Global Trade Analysis Project (GTAP). This version of GTAP consists of 129 regions and 57 sectors and has a base year of 2007. In order to make the computation of emissions taxes possible for China, we aggregate the database into 2 regions and 11 sectors. From [Labriet and Loulou \(2003\)](#), damages and abatement data are converted and apportioned accordingly to our 2-region, 11-sector aggregation of the GTAP database. The original GTAP regions are grouped into two new regions. The first region is China and all other regions are grouped as rest of the world. All sectors in GTAP have been grouped as services, electricity, transportation, manufacturing, mining & extraction, agriculture, food processing, construction & utilities, and textiles & clothing.

² For details on the GTAP version 8 database, interested readers are referred to the following link: <https://www.gtap.agecon.purdue.edu/databases/v8/>.

4. Methodologies

4.1. Computing optimal emissions taxes

Labriet and Loulou (2003) utilize optimization methods to calculate damages and abatement costs for various regions. We use shares from our 2-region, 11-sector aggregation of GTAP³ to adjust damages and abatement costs data in Labriet and Loulou (2003) to our 11 sectors.

If we assume that different income groups will value environmental damages differently, then the next stage in our procedure is to calculate the relative valuation of damages. Say for instance a given quantity of emissions is valued at \$1.00 by high income countries, we would assume that countries at the middle income level will prize emissions at \$0.5 and the same amount of emissions will be prize at \$0.2 by countries at the low income level. This can also be attributed to the difference in structure of the economy and uneven effects of environmental policies.

This means that one must first compute valuation for high income countries to be able to obtain absolute values. In order to do this, the conditions below must hold:

$$\pi_{ij} = \pi_i \quad (1)$$

π_{ij} in the equation above is the internalization rate⁴ of the i th sector in region j .

For any sector, Eq. (1) holds that, for each sector, similar rate of internalization should prevail for every region. Now, if the average internalization rate ($\bar{\pi}$) is 50% (Wesseh and Lin, 2016b), then it is possible to value damages caused by countries at the high income level and calculate the rate of internalization in each of the sectors considered. Going back to the definition of π_i , it is possible to obtain up to eleven identities which can be given as:

$$AB_i = \pi_i \times DE_i \times VAL(*) \quad (2)$$

Where AB is the costs of abatement, DE represents damages, $VAL(*)$ refers to emissions valuation in high income countries. These variables are represented in dollars (Perroni and Wigle, 1997). The internalization rate on average assumed to be 50% is calculated by:

$$\bar{\pi} = \frac{\sum_{i=1}^{10} \pi_i \times DE_i \times VAL \times Q'_{HI}}{\sum_{i=1}^{10} DE_i \times VAL \times Q'_{HI}} \quad (3)$$

Where Q'_{HI} is the output of GTAP sectors of countries at the high income level. To be able to derive all ten π_i as well as VAL or the "numeraire-evaluation", the procedures of either maximizing or minimizing VAL subject to all 11 equality constraints, as implemented in Wesseh and Lin (2016b) are followed. It is possible to obtain the solution for VAL because of the single element in the feasible set and π_i can be derived by utilizing (*). Before any shocks are implemented to the policy variable (s), the initial carbon taxes are calculated by:

$$T_{ij} = (RV_j \times Val^*) \times AB_i \quad (4)$$

Where T_{ij} is a representation of the benchmark carbon tax of the i th sector of region j , RV_j represents the relative valuation of emissions in the j th region and Val^* represents the manner in which countries at the high income level value carbon emissions in optimal terms. With this consideration, optimal carbon taxes are calculated from the equation below:

$$T_{ij}^* = \frac{T_{ij}}{\pi_i^*} \quad (5)$$

Where T_{ij}^* is a representation of carbon taxes in optimal terms of the i th

³ The GTAP model has recently been applied to study fossil fuels subsidies removal in Ghana (Wesseh and Lin, 2016c, 2017b).

⁴ The term internalization rate as used here refers to the cost share or fraction of environmental damages that is included in the production cost.

sector in region j and π_i^* is the optimal rate of internalization of environmental externalities of the i th sector. These optimal carbon taxes are then used to calculate the percentage change in the tax rates. This is given by the equation:

$$\dot{\pi}_{ij} = \frac{(T_{ij}^* - T_{ij})}{T_{ij}} \times 100\% \quad (6)$$

4.2. Incorporating abatement technologies into the GTAP model

This section begins by first presenting the GTAP⁵ model and what it initially includes. It then describes a generic production technology which represents abatement and shows how such technology could be mapped to GTAP. Finally, details on how specific abatement technologies are represented and implemented in GTAP are discussed. Essentially, the manner in which data on emissions and abatement expenditures (collected from Labriet and Loulou, 2003) and sectoral output (collected from the GTAP version 8 database) are applied to compute emissions taxes are described in Eqs. (1)–(6).

4.2.1. The GTAP model

The GTAP model is a multi-region CGE environment that emphasizes interactions between and among variables featuring policy instruments such as quotas, subsidies, taxes, etc. In addition, GTAP explains how various policy instruments are linked to employment, income and trade. A diagram showing the GTAP CGE model⁶ of global trade is given in Fig. 1. Analyzing environmental policy with GTAP is difficult because the model does not treat emissions and abatement costs explicitly. However, GTAP appears to be attractive for its comprehensive treatment of policy instruments⁷ and the detailed manner in which various sectors are disaggregated. As a result, if the GTAP model is used in combination with other related models, this would have the potential of providing more useful insights.

In GTAP, each good has the following production relationship

$$Q = \alpha_0 X \quad (7)$$

Where X in the above expression refers to the aggregate of inputs with price P_x and x represents input-output ratio. The connections between supply prices, market prices, taxes, and technical change in GTAP is given by (Perroni and Wigle, 1997)

$$ps = -\alpha_0 + pm + t_0 \quad (8)$$

Where pm is the proportional change in market price, α_0 represents the technical change parameter,⁸ and ps is the proportional change in the supply price. The 'shocks' to implement emissions charges in GTAP should be chosen in a manner that will satisfy conditions of equality between differences in the proportion of market input to output (pm , x) and the tax revenue for each unit of output.

4.2.2. Mapping between abatement technologies and GTAP

Whenever we consider abatement, the traditional approach is to use inputs to limit emissions linked to a specific amount of output (Perroni and Wigle, 1997). A production technology which represents abatement is given by

$$Q = f(X, E) \quad (9)$$

Where Q is output, X is the total amount of inputs in standard market

⁵ In the framework of GTAP (as we show in Fig. 1), there is a regional household with aggregate utility function that allocates expenditures across private (private household), government, and savings. The model user has some discretion over the allocation, that is, savings could be either regional or global.

⁶ For a more comprehensive explanation of the graphical structure of GTAP, interested readers are referred to Brockmeier (1996).

⁷ Policy instruments refer to variables like taxes, subsidies, quotas, etc.

⁸ Here, technical change parameter is a measure of any kind of shift in the production function.

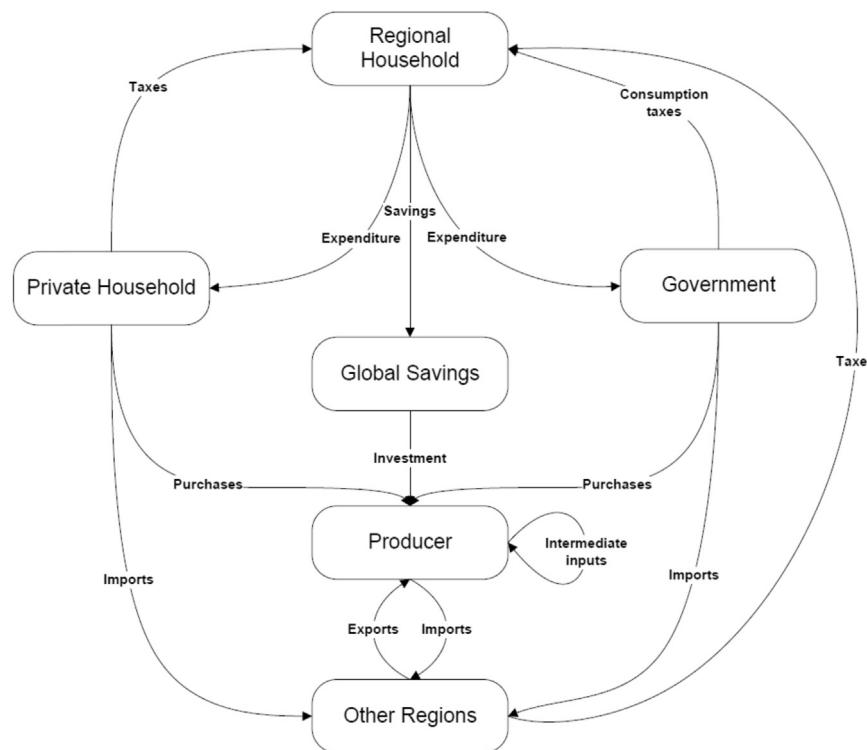


Fig. 1. The GTAP CGE model.

Source: Wesseh and Lin (2017a)

terms and E is the quantity of emissions derived from the production process. In this case, the price of emissions is the carbon tax and the cost per each unit of output depends on the price of market inputs (PX) as well as on the price of emissions/carbon taxes(PE). If we assume that the same equation form is used for the aggregate input X and inputs at market prices as demonstrative of the original model, it is possible to derive shocks for emissions taxes to the true model by imposing a functional relation $f()$ on the connection between Q , E and X . This can be done by imposing a shock on two variables in GTAP, that is, a neutral overall productivity shock (α_0) for each sector and a change in the power of output taxes(t_0).

For our purpose, we introduce three abatement technologies into the GTAP model. First, we incorporate a Cobb-Douglas abatement function into GTAP. Unlike the Leontief case, the Cobb-Douglas case creates the possibility of abatement by allowing for a fixed share between market inputs and emissions. Second, a Leontief abatement function is incorporated into GTAP. With this function, it is not possible to substitute between the level of inputs and the quantity of emissions. This implies that in order for abatement to be possible, there has to be a shift in the production technology. Finally, we also consider specification of $f(X, E)$ that are weighted averages of both the Leontief case and the Cobb-Douglas case.

4.2.3. Introducing a Cobb-Douglas abatement technology into GTAP

As we have mentioned, the Cobb-Douglas case makes abatement possible by allowing for a fixed share between market inputs and emissions. In this case, a 1% increase in carbon taxes would reduce emissions by 1%.

Market price in the Cobb-Douglas model is given by:

$$pm = (1 - \beta)px + \beta\dot{t} \quad (10)$$

Where \dot{t} represents change in the carbon tax and β is the parameter which denotes share of carbon taxes in total costs. Changes in per unit input requirements are then described by the following relationships:

$$\dot{x} = \beta\dot{t} \text{ and } \dot{e} = (\beta - 1)\dot{t} \quad (11)$$

Where \dot{e} refers to the change in emissions per unit of output.

In order for the price change in GTAP to be exactly the same as the price change in the Cobb-Douglas model, we should have the following equality:

$$\beta\dot{t} = -\alpha_0 - t_0 \quad (12)$$

From (11), we will also want:

$$\dot{x} = -\alpha_0 = \beta\dot{t} \quad (13)$$

Therefore, in order for (12) and (13) to be satisfied simultaneously, the only shock that will implement a change in carbon tax has to be done to the GTAP technology parameter, α_0 . Hence, in order to introduce a Cobb-Douglas abatement technology into GTAP, one has to apply the following shocks to the GTAP model:

$$\begin{cases} t_0=0 \\ \alpha_0 = -\beta\dot{t} \end{cases} \quad (14)$$

The corresponding change in emissions under Cobb-Douglas abatement due to the shocks in (14) becomes:

$$\begin{cases} \dot{e} = (\beta - 1)\dot{t} \\ \dot{E} = (\beta - 1)\dot{t}q_0 \end{cases} \quad (15)$$

Where \dot{E} is the change in total emissions, q_0 is the change in sectoral output, and all other parameters are the same as defined earlier.

4.2.4. Introducing a Leontief abatement technology into GTAP

Unlike the Cobb-Douglas case which allows for a constant substitution between X and E , in the Leontief case, no substitution is possible between X and E , and thus, abatement occurs only by shifting production.

To describe the Leontief case, it would be necessary to show how the ratio of the market input to output change. This change is represented by

$$\dot{x} = 0 \quad (16)$$

In order to make this ratio the same as the change that goes on in the GTAP model, the following equation is derived

$$0 = -\alpha_0 \quad (17)$$

Now, the market price under the Leontief model is given as

$$pm = px + \tau \quad (18)$$

Let S_x be a representation of the fraction of market inputs and S_e be a fraction of the emissions level. When (18) is differentiated and the shares $S_x = px/(px + \tau)$ and $S_e = \tau/(px + \tau)$ are applied, then the relationship between the change in minimum cost and the changes in τ under Leontief abatement is given by:

$$pm = S_x \cdot px + S_e \cdot \tau \quad (19)$$

One must not forget that in the initial situation, S_x would form a correspondence with $(1 - \beta)$ under the Cobb-Douglas scenario. On the other hand, S_e would be linked to β . As a result, in order to be able to make the changes in market prices the same in GTAP as in the Leontief model, the following items should hold

$$t_0 = -\beta\tau \quad (20)$$

Therefore, a Leontief abatement technology is introduced into GTAP by shocking the GTAP parameter corresponding to the change in the power of output taxes(t_0). These are given by:

$$\begin{cases} t_0 = -\beta\tau \\ \alpha_0 = 0 \end{cases} \quad (21)$$

The corresponding change in emissions under Leontief abatement due to the shocks in (21) becomes:

$$\begin{cases} \dot{e} = 0 \\ \dot{E} = qo \end{cases} \quad (22)$$

Since inputs, in Leontief production case, cannot be manipulated to reduce emissions for every unit of output, this study focuses on the situation where abatement is possible and easy compared with the Leontief production case but not as easy as the Cobb-Douglas production scenario. To implement this representation in GTAP, this study combines the Cobb-Douglas production function with the Leontief production function as presented below.

4.2.5. Introducing weighted Cobb-Douglas and Leontief abatement into GTAP

For the purpose of giving a more realistic representation of abatement substitution in the model, we design an experiment that assigns shocks to α_0 and t_0 in terms of weights from both Cobb-Douglas and Leontief production technologies. A fraction of 50% is considered for the weights from both technologies. From these calculations, the appropriate shocks to the GTAP model that would make for a representation of the combined case are given by:

$$\begin{cases} t_0 = -\frac{1}{2}\beta\tau \\ \alpha_0 = -\frac{1}{2}\beta\tau \end{cases} \quad (23)$$

The corresponding change in emissions under this weighted case due to the shocks in (23) becomes:

$$\begin{cases} \dot{e} = (1 - \omega_L)(\beta - 1)\tau \\ \dot{E} = \omega_L + (1 - \omega_L)(\beta - 1)\tau qo \end{cases} \quad (24)$$

For this weighted case, on which our results are based, shocks to the GTAP model for the i th sector in the j th region are computed.

4.3. Simulating environmental and welfare impacts of carbon taxes

In order to account for environmental benefits into our welfare calculations, a constant elasticity of substitution (CES) utility function

has been assumed for each consumer. Such a function is not only based on the standard utility aggregate, but it is also defined over the quality of the environment. This function is represented as

$$\hat{U} = F(U, Q) \quad (25)$$

F is the functional form of the CES utility, U is a representation of the equivalent variation that was estimated from the GTAP model, and Q describes the quality of the environment which is represented by

$$Q = \bar{Q} - D \quad (26)$$

In Eq. (26), \bar{Q} is used to measure the level of endowment attributable to the quality of the environment while D is used to describe the level of damages that are driven by emissions. In order to be able to quantify the level of damages in dollar terms, one has to first assume a constant rate for the extra damages coming from emissions and also the amount of emissions produced for every unit of output has to be known. For this purpose, it becomes necessary to assume two parameters. These parameters are, first, the fraction of initial damages in total endowments of environmental quality (D/\bar{Q}), and second, the elasticity of substitution in the CES utility function. For the first parameter(D/\bar{Q}), we assume a value of 0.25 for China and for the rest of the world. For the second parameter or the substitution elasticity, we assume a value of 0.5 for both regions. Using these parameters, we will be able to simulate the fraction of environmental protection in the utility function. From this variable, it is then possible to determine values for welfare.

4.4. Advantages and disadvantages of the applied model

Application of the GTAP model presents the following advantages: First, like many other CGE models, GTAP has a very large model size but requires a relatively small amount of data. This small data requirement is a direct opposite to standard econometric models which require observations for several years. Second, the GTAP version applied in this study has up to 57 sectors, and thus, grants the researcher a great flexibility on the choice of aggregation in order to suit his/her purpose. Finally, GTAP appears to be attractive for its comprehensive treatment of policy variable.

Despite these advantages, there are also a number of shortcomings associated with the applied model. First, because the model is estimated with data from a single reference year, estimates may be very sensitive to the choice of the reference year. Second, the applied model is static and ignores the dynamically evolving reality of the Chinese economy. Finally, analyzing environmental policy with GTAP is difficult because the model does not treat emissions and abatement costs explicitly.

5. Results

5.1. Emissions taxes

Pollution taxes under the benchmark are reported in the first column of Table 1. These can be interpreted as the emissions taxes per dollar output in the initial database. The results in this column show that constructed benchmark pollution taxes for China stand in the range of 0.81% for the mining and extraction sector and 0.19% for the service sector. When damages and abatement data are applied, optimal emissions taxes are computed and these findings are presented in the second column of Table 1. This time, the optimal emission taxes for China lie in the range of 2.02% for heavy manufacturing and 0.03% for the service sector. The optimal tax rates obtained for 8 out of the 11 Chinese sectors considered in this study stand well above the values of \$ 0.17 (or 0.17% per dollar output) and \$ 0.20 (or 0.20%) stipulated by the new Chinese environmental tax law due to take effect by January 2018. This implies that pollution taxes stipulated in the new law are less than optimal and should probably be revised.

Table 1
Calculated carbon taxes (cents per dollar of output).

Sector	Benchmark ^a	Optimal
Agriculture	0.42	1.09
Food Processing	0.266	0.10
Clothing and Textiles	0.3	0.76
Mining and Extraction	0.81	0.62
Light Manufacturing	0.30	0.79
Heavy Manufacturing	0.66	2.02
Construction and Utilities		0.39
Transportation	0.37	1.09
Electricity	0.51	1.26
Traded Services	0.19	0.03
Non-traded Services	0.19	0.03

^a Indirect taxes in the initial database.

Table 2
Change in sectoral production due to optimal carbon taxes (% change).

Sector	Coefficient
Agriculture	17.0
Food Processing	32.1
Clothing and Textiles	– 82.5
Mining and Extraction	– 7.2
Light Manufacturing	– 55.9
Heavy Manufacturing	– 20.6
Construction and Utilities	– 31.5
Transportation	30.9
Electricity	– 34.4
Traded Services	38.8
Non-traded Services	38.8

5.2. Emissions taxes and Chinese production

Estimates of how the implementation of carbon taxes affects Chinese sectoral production are reported in Table 2. These results show that implementing carbon taxes leads to increase in Chinese agriculture, food processing, transportation, and services. However, all other non-food sectors of the economy experience a decline in output when carbon taxes are introduced in China including the electricity sector. Foreshadowing these results, one would notice that the sectors with the largest carbon taxes imposed are those that experience the biggest changes.

5.3. Emissions taxes, welfare, and environment

Our first calculation of welfare excludes benefits from environmental cleanup.⁹ Because emissions taxes should be seen as forms of market distortions, their implementation should bring about a decline in welfare. This is especially the situation when the carbon taxes are unable to dissolve other preexisting distortions. Interestingly, even when welfare calculations do not reflect environmental improvement, carbon taxes still leads to welfare gains in China in the tone of approximately \$ 7.3 billion (Table 3). On the contrary, the rest of the world experiences welfare losses valuing about \$ 19.7 billion.

For a more realistic calculation of welfare we also report results in which environmental benefits are included with the model. In order to do this, the share (i.e. 15.9%) of climate protection in utility as presented in the left column of Table 3 for China is applied. Based on this value, the influence of carbon taxes on welfare, calculated to account for advantages associated with improvements in the quality of the environment, are shown in the right column of Table 3. The figure in parenthesis for China represents percentage welfare changes. These

⁹ Environmental cleanup refers to the quantity of emissions reduced as a result of implementing carbon taxes.

Table 3
Welfare computations.

Region	Share of environmental quality in total welfare (%)	welfare without environmental benefits (2007 \$ US million)	Welfare with environmental benefits (2007 \$ US million)
China	15.9	7329.1	35,448.7 (141.4)
Rest of the world	21.4	– 19,659	92,339

Table 4
Damages and environmental benefits (2007 \$ US million).

Region	Total value of damages before emissions taxes	Total value of damages after emissions taxes	Dollar value of environmental cleanup
China	90,113.2	33,816.3	56,296.9
Rest of the world	772,803.4	402,615.2	370,187.9

results show an increase in welfare from about \$ 7.3 billion when environmental benefits are excluded to approximately \$ 35 billion when welfare calculations include environmental benefits. In terms of share, the implementation of optimal carbon taxes in China increases welfare by 141.4%. As opposed to welfare losses for the rest of the world, including benefits from the environment with the simulations now creates welfare gains from carbon taxes in the amount of \$ 92.3 billion.

Lastly, Table 4 compares levels of pollution before taxes with the after-tax levels in order to quantify the environmental benefits from carbon taxes. Seeing from Table 4, there appears to be enormous benefits both for China and for rest of the world when carbon taxes are implemented. In particular, pollution is reduced by 62.5% for China and by 48% for the rest of the world. The calculated value of environmental cleanup for China amounts to \$ 56.3 billion while that of the rest of the world is \$ 370.2 billion.

6. Discussion

Results from computing optimal emissions taxes, and testing their economic and environmental impacts, presents interesting policy implications for China.

First, it is interesting to note that manufacturing accounts for the heaviest tax rate in China and the implementation of these taxes leads to decline in output of manufactures. According to 'STATISTA,¹⁰ in 2016, 27.7% of Chinese workforce were employed in agriculture, 28.8% in industry and 43.5% in services. Although the implementation of carbon taxes in China results in general welfare gains, reduced output in manufacturing could cause severe job losses and thereby result in unemployment issues due to the large percentage of employed workers in the industrial sector. For this reason, it would be necessary to introduce carbon taxes in tandem with policies aimed at boosting the labor market, especially in manufacturing.

Second, giving that carbon taxes are not only associated with welfare gains, but also serve to significantly reduce environmental pollution, the implementing of these taxes become a useful policy instrument for China and their importance should not be overemphasized.

Third, since carbon taxes are not a sufficient tool for mitigation in China (because they reduce pollution only up to 63%), the development and diffusion of renewable energy and nuclear energy into the Chinese fuel mix becomes an attractive option for China's mitigation goals. In

¹⁰ Interested readers are referred to the following page for more details: <https://www.statista.com/statistics/270327/distribution-of-the-workforce-across-economic-sectors-in-china/>.

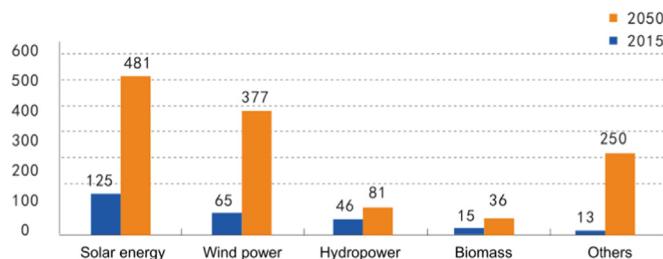


Fig. 2. Renewable energy employment creation (10,000 people).

Source: EFC (2015)

fact, China is home to a variety of renewable energy resources and reserves including nuclear energy resources. As a result, exploring options and research into the potential of optimal clean energy expansion and diffusion into the Chinese fuel mix becomes necessary. It is also important to mention the importance of renewable energy for Chinese job creation. As we show in Fig. 2, there appears to be a remarkable increase in job creation from various renewable energy sources between the year 2015 and the year 2050. This implies that a widespread deployment of renewable energy technologies would be a good strategy not only for mitigating carbon emissions, but for also addressing the unemployment issues associated with the implementation of carbon taxes.

Fourth, it is also interesting to note that the results reported in this study have shown that the implementation of carbon taxes in China would lead to a decline in output of the electricity sector. Since the applied dataset has a base year of 2007 in which 81% of Chinese electricity came from coal that year (IEA, 2009), it is not surprising why a high carbon tax rate has been obtained for the electricity sector in this study (Table 1). The corresponding decline in electricity supply due to this high tax rate (Table 2) also serves as a strong motivation for the expansion of clean energy technologies. The logic is that, if fossil-driven electricity is heavily taxed due to the associated high carbon intensity, then the corresponding fall in output should be offset by 'clean electricity' which are less prone to carbon taxes.¹¹

Finally, there appears to be substantial differences in magnitudes of the estimates reported in this study and those in Wesseh and Lin (2016b). These differences in results, especially for China, are likely due to the fact that the assumption that abatement data for the United States could be used as a proxy for China is somehow strong and unrealistic. Hence, this suggests that energy and environmental modeling should be based solely on country-specific data.

7. Conclusions and policy implications

7.1. Conclusions

In this study, attempts have been made to model the Chinese carbon tax policy. In order to do this, we combine abatement technologies with the GTAP CGE model to first compute optimal carbon taxes and subsequently test their economy-wide and environmental impacts for China.

Computed taxes are highest for heavy manufacturing and lowest for the service sector. Implementing carbon taxes increases agriculture and food processing, but reduces output of most of the non-food part of the economy including the manufacturing and electricity sectors. In general, the imposition of carbon taxes in China increases welfare by 141.4% when environmental benefits are included with the simulations. In addition, damages done to the environment are reduced by

approximately 63% for China and 48% for the rest of the world when these taxes are imposed. Calculated value of environmental cleanup for China amounts to \$ 56.3 billion while that of the rest of the world is \$ 370.2 billion.

7.2. Policy implications

Based on the discussion documented in Section 6, the results of this study demonstrate that carbon taxes are important for China as they increase welfare and reduce environmental pollution. Notwithstanding, the following policy implications can be drawn. First, since carbon taxes reduce output of key Chinese sectors including manufacturing, these fees should be implemented in tandem with policies aimed at boosting employment. Given that clean energy deployment tends to provide opportunities for job creation, carbon taxes should as well be implemented with clean energy expansion policies. Hence, clean energy expansion serves as a double win – mitigation and job creation. Second, the results show that carbon taxes are not sufficient for mitigation suggesting the need for China to continuously explore options and research on the potential for optimal clean energy expansion and diffusion into the Chinese fuel mix. Finally, differences in parameter estimates of the current study and those in Wesseh and Lin (2016b) suggests that energy and environmental modeling should be based solely on country-specific data.

7.3. Limitations and avenue for further research

Despite the contribution of this study, there are also few shortcomings that should be taken into account when interpreting the results reported. First, because the model is estimated with data from a single reference year, estimates may be very sensitive to the choice of the reference year. Second, the applied model is static and ignores the dynamically evolving reality of the Chinese economy. Finally, analyzing environmental policy with GTAP is difficult because the model does not treat emissions and abatement costs explicitly. Addressing all of these issues and narrowing the discussion to a single Chinese sector using newer datasets appears to be a valuable avenue for further research and model improvement.

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¹¹ Lin and Wesseh, 2013b show that the extent to which electricity use is successful in reducing carbon emissions is largely due to the extent to which electricity is generated from clean sources. And this could also be based on the degree of price volatility in primary sources (Lin et al., 2014, Lin and Wesseh, 2013c).

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